ABSTRACT

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A study is being conducted to determine if tracking data from earth-based radars can be used to establish the position and velocity of a spacecraft in lunar orbit with enough precision to supplement or backup on-board guidance and navigation devices.

It appears at this stage that earth-based tracking data will be useful and the study is expected to supply a quantitative estimate of the accuracy which can be obtained as a function of the various system parameters and the spacecraft orbit.

With the adoption of the lunar rendezvous concept for Apollo, there has been a renewed interest in the ability of the ground tracking facilities to support operation in the vicinity of the moon. In particular, it is desirable to know how well ground tracking can supplement or back up the onboard navigation and guidance systems when the spacecraft is in a lunar orbit. This problem is similar to the classical astronomical problem of determining the orbit of spectroscopic binaries. These are binary systems close enough together to be beyond the limits of resolution of even the finest telescopes. Astronomers determine from the spectroscopic doppler shift the period, semi-major axis, eccentricity, and the angle between the line connecting components of the binary system and the line-of-sight. The angle between the normal to the orbit plane and the line-of-sight can be estimated from luminosity data. This determines the orbit except for a final angle about the line-of-sight which remains indeterminant in all but a few special cases.

In the case of earth-based tracking of a vehicle in lunar orbit, angle tracking information is useless, since even 1/10 mil. represents some 20 miles at lunar distances. With reasonable signal-to-noise ratios, however, the random components of range and range-rate measurements are similar to those experienced when tracking objects near the earth. One would expect, therefore, that the orbital elements of a vehicle in lunar orbit could be determined quite well from a moderate amount of good quality range and range-rate data, except possibly for an ambiguity about the line-of-sight.

The relative motion of the earth and moon may allow this final angle to be determined, but since this motion is slow, the necessary observation periods may be fairly long, perhaps even greater than the period during which the satellite is in view during one revolution. If this proves to be the case, a great improvement could be expected with the inclusion of *a priori* information, such as the bearing of a particular lunar crater from the spacecraft or the distance from the spacecraft to a beacon located at a known position on the lunar surface.

Another difficulty with earth-based tracking of lunar orbits is that biases due to the uncertainty of our knowledge of the velocity of light are introduced in both the range and range-rate measurements. The bias of range is proportional to the range and at lunar distances may be as much as a half mile. The bias in the doppler measurement is correlated with the bias in range and varies throughout the lunar orbit. While one would expect a constant bias to have little effect on the determination of the lunar orbit, the correlation between the biases and the variation of the doppler bias may degrade the accuracy of the ground-based estimate of orbital elements substantially.

With these misgivings about the capability of ground tracking to determine lunar orbits, it seemed advisable to avoid a major investment in programming and computer time until some rough estimates of the capability could be made. On the other hand, it was clear that the problem could not be simplified to a point which would allow hand calculations in a reasonable time without losing the significance of the results. A survey was made of existing computer programs and it was found that while none were really appropriate, PATE I might be used to obtain at least enough information to decide whether it was worthwhile to pursue the problem further

In order to use this program, however, a number of simplifications and assumptions had to be introduced. The most significant of these were:

1. The spacecraft was influenced only by the gravitational attraction of the moon which was assumed to be that of a point mass.

2. The moon was assumed to be in a circular orbit about the earth at the moon's mean distance.

3. Earth rotation was neglected.

4. The radar site was assumed to be at the center of the earth.

Even with these simplifications, questions remained concerning the accuracy of the program. To insure that the results would be trustworthy, a series of tests were made and the problem was carefully scaled. In addition, a special case, which can be calculated analytically, is being programmed in double precision Fortran and will be compared with the output of PATE I before results should be considered trustworthy.

One significant aspect of the problem, however, cannot be handled with the present PATE I. While constant biases may be included in PATE I, they are ignored in the processing. This is satisfactory for many problems leading as it does to conservative estimates of capability. The bias in the doppler measurements, however, cannot be considered a constant and so cannot be included in any analysis based on this program.

With these qualifications the results of tests of PATE I to date have been encouraging, both from the point of view of confidence in the program and the ability of earth-based radars to estimate lunar orbits. The results of a typical run are given below. The coordinate system is rectangular with the origin at the vehicle, the x-axis in the direction of the velocity vector, the y-axis perpendicular to the velocity vector and in the plane of the orbit, and the z-axis chosen to complete an orthogonal triad. For this run no bias errors were included. The radar was assumed to track the spacecraft during the entire time it was visible from earth during a single orbit. This was a period of about 76 minutes.

$\sigma_r = 60$ ft $\qquad \sigma_{\dot{r}} = 1$ ft/sec $\qquad$ Sample rate - 1/sec

$\sigma_x = 1410$ ft $\qquad \sigma_{\dot{x}} = .015$ ft/sec

$\sigma_y = 304$ ft $\qquad \sigma_{\dot{y}} = .89$ ft/sec

$\sigma_z = 4080$ ft $\qquad \sigma_{\dot{z}} = 2.35$ ft/sec

$\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} = 4400$ ft. $\qquad \sqrt{\sigma_{\dot{x}}^2 + \sigma_{\dot{y}}^2 + \sigma_{\dot{z}}^2} = 2.54$ ft/sec

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The same run was repeated with no relative motion of the earth-moon system. As expected, the resulting ambiguity prevented an estimate of position and velocity of the spacecraft in this coordinate system.

We are now preparing a series of cases which will allow us to investigate with PATE I the effects of biases in range, changes in orbital elements, sampling rates, tracking interval, and the random components of measurement errors.

Should the results warrant, we will construct a new program based on a more realistic model of the earth-moon system in which we will be able to include realistic biases and to use more nearly optimum processing to reduce the data.

AJM:r

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